UNITED STATES PATENT APPLICATION

of

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for

RECONFIGURABLE MICROPHOTONICS DEVICES VIA DEFORMABLE MEMBRANE PLATFORMS

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PRIORITY INFORMATION

5   This application claims priority from provisional application Ser. No. 60/395,932 filed July 12, 2002, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

The invention relates to the field of microphotonics, and in particular to

10   reconfigurable microphotonic devices via a deformable membrane platform.

The vast majority of microphotonic devices possess a wide spectrum of applications. Most of these devices are static devices, where reconfiguration is not possible after device fabrication. To achieve tuning of microphotonic devices, the electro-optic effect, the charge-carrier effect (via temperature and/or doping) and the

15   liquid crystal tuning methods have been reported. There is a need in the art to provide tunability in silicon microphotonics, given the absence of electro-optic effect in silicon. Our invention also permits low-power actuation, a response time on the order of 10^{-5} sec, and fine-resolution control of the tuning.

20 SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided a microphotonic device. The microphotonic device includes a membrane structure that can experience strain. A waveguide element is formed on the membrane structure so that when the membrane structure is strained, the waveguide elements are tuned to a selective amount.

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According to another aspect of the invention, there is provided a method of forming a microphotonic device. The method includes providing a membrane structure that can experience strain. Also, the method includes forming a waveguide element on the membrane structure so that when the membrane structure is strained the waveguide

5   element is tuned to a selective amount.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic diagram of a microring resonator implemented on top of a membrane; FIG. 1B is a flowchart demonstrating how to fabricate the microring

10   resonator;

FIG. 2 is a schematic diagram of a microracetrack resonator implemented on top of a membrane;

FIG. 3 is a schematic diagram of a higher order microracetrack resonator implemented on top of a membrane;

15   FIG. 4 is a schematic diagram of a microcavity waveguide implemented on top of a membrane; and

FIG. 5 is a schematic diagram of a 2-dimensional photonic crystal implemented on top of a membrane with 1-dimensional tunability.

20   ## DETAILED DESCRIPTION OF THE INVENTION

The invention uses a novel concept of tuning microphotonic devices via mechanical deformation. A microphotonic structure, such as a microring resonator, a photonic crystal, or similar derivatives can be superimposed onto a thin sub-micron

deformable membrane. The controlled deformation of the membrane will allow the geometrical structure to be tuned up to the order of 0.2% strain. Correspondingly, optical properties of the microphotonic structure, such as resonance in the bandgap of the transmission spectra, the size of the bandgap, the quality factor Q of a quantum

5   electrodynamics cavity, and other properties can also be tuned. Fine control of the membrane deformation will allow fine-tuning of these optical properties.

This invention will also allow for dynamic tuning of these properties, either in part of the device function, in response to fabrication deviations, or to external disturbances. Real-time reconfigurability of the microphotonic structures can be

10   achieved. This invention uses the concept of deformable membrane actuation to mechanically tune microphotonic structures.

FIG. 1A shows a microring structure 2 that is formed on a membrane 6 supported by base anchors 7. The thin-film membrane 6, sub-micron in size and on the order of 200 − 400 nm, is deformed through thin-film piezoelectric actuators 4, such as lead zirconate

15   titanate (PZT), poly-vinylidene fluoride (PVDF), zinc oxide, quartz or aluminum nitride. With the mechanical strain through the piezoelectric actuators 4 that has the high power density on the order of 1000 W/kg, the piezoelectric actuators 4 provides a possible and experimentally measured strain of approximately 0.2% on the membrane. With a super-imposed microphotonic device structure, this 0.2% tunability in the structure results in

20   changes in its optical response. The base anchor 7 on both sides of the membrane provides the fixed-fixed boundary supports to the deformable membrane.

For a photonic crystal bandgap with a defect, such as in a 1-dimensional photonic crystal microcavity waveguide, this mechanical strain creates a 0.56% change in the

resonant frequency in the transmission bandgap from modified perturbation theory computations. For a 2-dimensional photonic structure, the membrane can be designed to limit the strain at the line defect.

The maximum amount of deformation will be limited by the strain limit of the membrane and the actuators. For lead zirconate titanate (PZT) piezoelectric actuators, the actuator strain limit could reach up to 0.1% and provide a membrane strain on the order of 0.2%. The membrane is a thin sub-micron silicon oxide (SiO_2) layer to provide mechanical support for the microphotonic structure, while providing high dielectric contrast with air underneath the membrane. A suggested thickness of 200 nm is designed under mechanical robustness constraints. If the microphotonic structure is continuous in the strain direction, the strain limit of the microphotonic structure is highly dependent on the surface roughness of the material; a silicon material with surface roughness below 20 nm is expected to have fracture stresses on the order of 1 GPa, corresponding to a strain limit of 0.7%. The device strain limit is dependent on the detailed microfabrication process, dependent on the geometrical shape of the structure in introducing stress concentration regions, and expressed as a probability distribution function through Weibull statistic. The strain of 0.2% to 0.3% for the silicon devices in our invention is a safe estimate.

The steps of fabricating the inventive microring device are shown in FIG. 1B. A microphotonic device is fabricated on top of a SiO_2 membrane layer (step 10). A Pt/Ti layer is deposited and lift-off patterned to from the bottom electrode for the PZT (step 12). The thin-film PZT is deposited, annealed, and wet etched (step 14). A Pt/Ti layer is deposited and lift-off patterned to form the top electrode for the PZT (step 16). A SiO_2

membrane layer is patterned via Reactive Ion Etching (step 18). Frontside XeF$_2$ etching

or backside Deep Reactive Ion Etching is used to remove bulk Si substrate to free the

membrane (step 20).

Step 10 is a lumped fabrication step to create a microphotonics device and

5   depends on the exact device. Steps 12-16 create the active piezoelectric actuators. Steps

18-20 create the doubly-anchored deformable membrane platform for microphotonics

devices.

Microring resonators have applications in channel dropping filters and can be

made compact for high-density integration and low loss through high dielectric contrast

10 waveguides. By applying a mechanical strain on the microring resonator, the optical path

length of the microring is changed, resulting in tunability of the resonant mode.

In a second embodiment of the invention, a microphotonic structure 24 includes a

microracetrack resonator 30 that is implemented on top of a membrane 28, as shown in

FIG. 2. With identical applications to the microring resonator 8 shown in FIG. 1A, the

15 microracetrack resonator 30 allow for more efficient coupling because the straight length

32 of the racetrack 30 allow for exact phase-matching between the input/output

waveguides and the microphotonic structure 24. By applying a mechanical strain on the

microracetrack resonator 30, the optical path length of the microracetrack resonator 30 is

changed, resulting in tunability of the resonant mode. Furthermore, the techniques for

20 fabricating the microphotonic structure 24 is the same steps for fabricating the

microphotonic structure 2, as discussed for FIG. 1B, except the dimensions of the

microracetrack resonator 30 will be different than that of the microring structure 8

discussed in FIG. 1A.

Tuning of a microracetrack resonator via mechanical deformable membranes is especially useful for higher order filters, as shown in FIG. 3, where virtually identical resonances are necessary for acceptable efficiencies in the higher order filters 34. Via mechanical deformation, as opposed to thermal tuning, localized tuning of individual

5 resonators is now possible. Higher response times and lower voltage requirements are also essential benefits.

In another embodiment of the invention, a microphotonic structure includes a microcavity waveguide 40 that is formed on top of membrane 38, as shown in FIG. 4. This waveguide 40 is a 1-D photonic crystal, with optical confinement in the other two

10 directions through total internal reflection from the high dielectric contrast in the silicon waveguide. By mechanically-straining the membrane with piezoelectric actuators 44, the defect length over the lattice constant ratio can be increased. Based on design analysis and demonstrated experimental work, a strain of 0.1% to 0.2% can be applied at the microcavity and a strain of 0.2% to 0.3% at the holes 42 in the waveguide. A mechanical

15 strain of 0.3% on the microcavity waveguide will result in approximately 0.85% tunability in the resonant frequency in the bandgap, as calculated through perturbation to finite-difference time-domain computations. The specific amount of tuning in the periodicity could be increased and decreased in specific designs.

In another embodiment of the invention, tuning of fractional edge dislocations 52

20 for 1-dimensional deformation of a 2-dimensional photonic crystal 46, such as a hexagonal 2-dimensional photonic crystal with a line defect 52, is shown in FIG. 5. The strain can be concentrated at the fractional edge region 48 through sharp width tapering of the membrane 50 at the fractional edge region 48, leading to significant mechanical

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strain at the localized region. The removal of membrane material along the line defect permits localized strain at the fractional edge region 48. By tuning the localized period in this example photonic crystal 46, the Q factor of the localized mode from defect 53 of the photonic crystal 46 can be increased. Furthermore, FIG. 5 shows that the photonic crystal 46 has a length of L_2 and the length of the fraction edge region 48 is L_1. Note that the PZT actuation is used in operation of this structure.

The inventive microphotonic structure can be used in optical circuits and optical communications, such as tunable vertical 2-dimensional photonic band-gap defect laser. Moreover, the inventive microphotonic structure can be used in light modulation for optical displays and optical storage devices. Furthermore, the inventive microphotonic structure can be used in experiments in cavity quantum electrodynamics.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is: